Combustion Sensors: Gas Turbine Applications

A Final Report submitted to NASA Ames Research Center Grant# NAG 2-1430

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EXECUTIVE SUMMARY

This report documents efforts to survey the current research directions in sensor technology for gas turbine systems. The work is driven by the current and future requirements on system performance and optimization. Accurate real time measurements of velocities, pressure, temperatures and species concentrations will be required for objectives such as: combustion instability attenuation, pollutant reduction, engine health management, exhaust profile control via active control, etc. Changing combustor conditions – engine aging, flow path slagging, or rapid maneuvering - will require adaptive responses; the effectiveness of such will be only as good as the dynamic information available for processing. All of these issues point toward the importance of continued sensor development. For adequate control of the combustion process, sensor data must include information about the above mentioned quantities along with equivalence ratios and radical concentrations, and also include both temporal and spatial velocity resolution. Ultimately these devices must transfer from the laboratory to field installations, and thus must become low weight and cost, reliable and maintainable.

A primary conclusion from this study is that the optics based sensor science will be the primary diagnostic in future gas turbine technologies. Accordingly, these techniques dominate the following discussions. The various procedures involve some type of illumination of the flow filed, and subsequent signal interrogation. While "classical measurement devices will still have usage, it is believed that laser driven system provides the overall performance and responses which will be required by the mentioned system objectives. Particle Image Velocimetry (PIV) allows velocity time measurements over a region of space. Planar Doppler Velocimetry (PDV) and Phase Doppler Particle Analysis (PDPA) are similar to PIV, but demonstrates superior three dimensional resolution due to a use of the scattered particle's frequency shift. Further advances in laser and camera technology will enhanced its effectiveness. Laser Doppler Anemometry (LDA) also allows instantaneous flow rate determinations, and is particularly effective for assessing injection droplet velocities, sizes and number densities. Phase Doppler methods involve information processing of laser generated fringe patterns, and has the advantage of not requiring calibration, a potentially significant advantage in field applications. The scattering analysis is further exploited by, Filtered Raleigh Scattering (FRS), where vapor filters are used to suppress background noise, and allow more accurate estimates of quantities such as temperature fields. Investigators have used this technique to measure temperature in a combustion environment, and the simultaneous measurement of density, temperature, pressure and velocity. Laser Induced Incandescence (LII) involves invoking a radiant response by the heating of target particle surfaces, and subsequent data processing via charge coupled device (CCD) techniques. It has proven to be effective in determining soot concentrations in exhaust streams an important result, as soot is a good indicator of combustion efficiency. The observation of chemiluminescent emissions from particular species in exhaust gases can lead to conclusions about combustion energy release rates and zone equivalence ratios. Very promising results have shown how the relatively rugged diode laser can be incorporated in systems for harsh environments.

The research efforts in these areas show great promise. However, there appears to be a relative dearth of information concerning actual implementation in gas turbine systems. Issues to be resolved include the size, complexity and ruggedness of these devices. Thermal, shock and vibratory environments in real world systems will be more severe than laboratory conditions. Limited optical access, restricted geometry, background luminosity, spectral interference, and fully developed turbulence, are all issues, which will require attention.

Line of sight geometry must also be established in very constrained flow passages. Field system implementation and cost reduction are significant issues for consideration.

A major area for investigation is defining exactly how these advance systems are to be used. System performance, health monitoring, active control are all candidate objectives. The actual usage will influence what variables are to measured, where such interrogations must be performed, and to what accuracy and bandwidth. Accordingly, a major recommendation is reviewing the gas turbine system role and initiating and continuing: in-depth investigations for establishing objectives and associated measures of merit, defining system architecture, and performing simulation studies. This will assist in answering a number of questions about sensor requirements and expected performance.

In addition to the optical systems, a short discussion is done on acoustic and electromagnetic methods; these techniques could also prove useful in specific applications.

I Background

Performance levels for new generations of prime movers, of special interest here - gas turbine systems will have to meet higher levels of requirements. The challenge is a formidable one as it involves the simultaneous and somewhat conflicting tasks of improved thermodynamic performance and reduction in polluting emissions. Obtaining these enhancements in performances will rely significantly in the ability to monitor, measure and control various processes throughout the flow path. Accordingly there will be great need for high fidelity sensor devices and the corresponding data fusion methodologies for optimizing engine parameters.

The ability to continuously monitor the physical and chemical environments associated with combustion processes is and will be an important function in the energy and propulsion technology areas. These diagnostics provide information for supplementing the understanding of the chemical kinetics; specie consumption and depletion rates and data input for real time applications such as active control.

The development of digital control modules along with microprocessor capabilities have positively impacted the aviation and gas turbine engine community with the capacity to improve performance and reliability of such systems (Alden-99, Eckbreath-96, Gord-01, Kiel-01, McManus-93, Schadow-96, Zinn-97). Sensors are essential for active control using state feedback methodologies. Combustor control requires devices that can respond to fluctuations in heat release rate, variations in local fuel-air ratio, and temperature estimates at the exhaust plane. For aero-gas turbine engine applications, control of combustor exit temperature, combustion instabilities, and pollutant emissions are desirable control goals, all, which require accurate real time data streams. New techniques in engine health monitoring will require real time and historical data recording.

Chemical reactions such as combustion processes are dependent on the relative composition on the reactants, the initial thermal state - temperature and pressure, the presence of any catalytic substance, and the physical dynamics of the initial state such as a fluid velocity. In real processes while these parameters may be initially known, as the process proceeds measurements must be taken to constantly monitor the reacting environment. It is a complex coupled phenomena where effects of the reactions such as exothermic energy release impacts the environment which in turn influences the reactions, etc., etc. Real time data acquisition is imperative in the understanding of the process evolution and sensitivity of the reactant-product dynamics with respect to the controlling factors.

Advances in the improvement of gas turbine systems are strongly linked to greater understanding about the physics and chemistry of multiphase turbulent reacting flows. Current research areas such as supersonic combustion, pollutant and soot formation, turbulent combustion and interactive control will continue to rely heavily on real time temperature and chemical sensing along the flow path environment. Higher performance requirements (up to 4000 F temperature and 30-40 ATM, pressure) will demand accurate scaling and design laws that may be confirmed only from actual measured data. Higher fidelity validation and benchmarking of computational fluid dynamics codes used in engine analysis and design will require more accurate measurements. Turbulent closure of these models may also be assisted by such data. Automonous and ongoing health management for engine and vehicle require accurate evaluation systems. This will lead to reduced maintenance and life cycle costs.

Laser based methods such as CW high-resolution spectroscopy and ultra-fast spectroscopy will are prime candidates for the task of real time non-intrusive temperature, velocity vector, and specie concentration assessments in gas turbine systems. Improvements must be made to current Doppler and anemometry velocity measurements as they involve bulky systems unsuitable for field usage. Specie measurement is less practical as procedures such as absorption, laser induced florescence and Raman scattering are even more complex.

Traditionally, measurements are considered as either intrusive or non-intrusive. Intrusive techniques, such as hot wires and Pitot tubes while fairly accurate, interferes with the flow and does not provide spatial resolution (Fraden-97).

High sensitivities are needed in many applications. For example, scramjet engines generally exhibit relatively small end to end increase of momentum flux. Thus proper thrust measurements require high accuracy estimates of density, temperature and velocity. Injection systems involve phenomena such as jet instability, fuel droplet coalescence and disintegration, impingement and gas spray interaction. For accurate estimates, one must couple both downstream and upstream oscillating flows.

Clearly, both experimental research and actual field implementation will benefit from continued advancements in sensor technology.

II Traditional Sensor Devices

In this chapter, we briefly discuss traditional or "classical" methods for measuring velocity, pressure, flow and temperature.

Velocity, Flow and Pressure

Pitot tubes are well known instruments for velocity measurements, using Bernoulli's principle for pressure-velocity head conservation (Moore-65). However they present obstruction issues and can only be used when this is not a problem. Also they can only withstand moderate thermal conditions.

Venturi meters are standard flow measurement devices (Baker-81).

Pressure measurement devices generally rely on one of three basic ideas: comparison of equivalent heights of a known liquid, measuring force acting on a given area, or determining some pressure correlated physical of property change in a substance. Common instruments employing the first two methods include manometers, Bourdon and diaphragm gages (Benedict-77). An example of the third type is either the Pirani or thermocouple gage (Moore). Utilizing the change in conductivity with respect to pressure, the current changes in a heated wire are measured and correlated.

Pressure sensors have the capability for monitoring fluctuations for combustion instability control although their temperature sensitive calibration characteristics complicate the application. In addition, they cannot withstand combustor liner temperatures and therefore must be encapsulated which interferes with reading integrity.

Thermal anemometry (TA) (III- measures fluid velocity by sensing changes in heat transfer from an electrically heated wire or thin film exposed to the fluid. Anemometers are generally classified as either constant-current or constant-temperature, although recent developments of constant voltage devices may make that mode prevalent (Kegerise-00). A control circuit maintains the wire at a constant temperature. Convective transport, which is proportional to the velocity, cools the wire; the required current adjustment for constant temperature is measured and calibrated. Advantages include low cost, flexible applications and ready automation. TA is also has utility when fast response time is needed.

Clearly there are limitations in the in-situ positioning for engine applications. The technique can be applied to most "clean" flows where the intrusion of the sensor does not adversely impact the flow field. These systems have deficiencies with respect to bandwidth, sensitivity and signal to noise ratio, which limits their applicability to high speed, high Reynolds numbers flows. Also as just mentioned, contaminates can degrade or damage the relatively fragile sensors. A low level of turbulence is also a desire operational requirement, although some studies have focused on extending the applicability against this shortcoming (Ljus-00).

For enhancing the single point statistics of three dimensional flow fields, methods of using two or more probes have been developed (Maciel-00). Cross wire techniques are the most commonly used, although they suffer from relatively long measuring times, inability to resolve simultaneous three component velocities, and variable unsteady flows.

Studies have been performed which unite anemometry methods with laser based devices (Dawson-91). Dynamic calibration is difficult for the frequency dependent hot film probes; instead corrections involving turbulent energy spectrum has been investigated, particularly in the area of gas-particle flows.

Temperature

Temperature measurements are often performed with thermocouples. When two wires of dissimilar materials are joined at two ends which are exposed to two different temperatures, a continuous circuit is established – the Seeback effect. The current magnitude is a function of the temperature difference between the wires, in addition to the specific materials. In actuality the Seeback voltage is the measured quantity, and it must be calibrated accordingly.

Several factors must be areas of concern when using thermocouples. Positioning of the thermocouple is critical as to correctly measure the intended location. They are unsuitable for insertion into high temperature gas flows, recent experiments at elevated temperature has exposed significant durability issues (Delaat-00). Thermowells and protective tubes could extend usage for harsh environments; embedding in structural elements may be done for obtaining wall temperatures. Care must be taken that the device's presence does not disturb the flow environment as to give inaccurate estimates to what is truly going on.

Thermocouple arrays are often located between high and low pressure stages as combustor exit temperatures prohibits their use at those positions. While this serves to assist in providing engine health

monitoring and ignition detection, this application is unable to resolve time lags between combustion chamber and sensor location events. As flow has just left the high pressure turbine, flow data representing combustor conditions has been distorted. Inaccuracies due to stagnation pressure and gas dissociation losses misrepresent upstream temperature profiles. Poor mixing is also not captured.

However, the importance of thermocouples should not be diminished. Whenever their inherent intrusive nature is not a factor, they are excellent measurement devices. They have been used as diagnostic tools in turbulent gaseous and spray flames. They are often used as calibration instruments for laser sensors. Response time may be improved by grounding the junction to a protection device. Some temperature measurement results have been favorably compared with those given by laser Raman spectroscopy, and indeed may be superior to lasers on sooty flames and when high sampling rates are required. Recent work has been performed in temperature ranges of 2100-2700 K, which is traditionally beyond thermocouple application (Gokoglu-00). The technique involves monitoring the sharp increase in emittance of certain metal oxide fibers as the material approaches known melting points. In this regime, greater care must be taken for temperature correction, due to enhanced radiative losses.

Another temperature measuring device is the optical pyrometer. A lens focuses unto a calibrated tungsten filament. The light intensity on the filament is kept constant by maintaining a constant current flow. An optic wedge is positioned in the target light path until the two intensities appear to be equal, and the calibrated temperature is read. In a similar configuration, the radiation pyrometer uses a sensing element instead of a filament. This device is useful for temperatures in excess of 800 K., As it is a non-contact apparatus, the pyrometer is useful for measuring moving, remote, or inaccessible objects or surfaces.

Radiation thermometers estimate temperature by measuring the radiative emissive power of the source over a wavelength bandwidth. It can be shown that higher emissivity surfaces give more accurate readings. Accordingly, coating the targets with thin layers of low reflectance materials improve this application.

Specie Concentrations

Techniques have been developed for the simultaneous measurement of flow velocity and concentration fluctuations, using a dual hot wire sensor (Sakai-01). A digital data processing algorithm uses the voltage from both sensors and a calibration map. Construction of the probe depends on the conductivity of the specimen gas. The procedure utilizes the so called overheat ratio (OHR), and has the advantage of not requiring constant adjustments of the OHR.

Surface mounted hot-film sensors can also be used to obtain pressure recovery values (Jones-01). Results show that high mean and low level rms voltages correlate well with improved pressure recovery. The procedure is also useful for determining flow distortion levels.

While not a typical measurement in gas turbine applications, active control efforts may be assisted with real time air stream humidity determinations, giving the not insignificant effect water vapor has on system performance. Psychrometers and hygrometers are standard instruments for humidity measurements. For engine applications, an electronic sensing device is needed. For example, a coil impregnated with a hygroscopic salt demonstrates a humidity dependent resistance where the resulting current can be calibrated to water content values. Similar devices for other gases use Wheatstone bridge circuitry for determining concentrations, which affects the medium's thermal conductivity.

Other

While not a direct input in combustion control schemes, knowledge of turbulence statistics improves fundamental understanding of flow field behavior and thus could influence gas turbine design thought. Hot wire anemometry, particularly multi wire probes have been used for assessing three dimensional velocity fields along with Reynolds stress estimates (Chen-00).

III Optical Methods

In this chapter, we discuss recently developed sensor efforts, namely laser based systems. Non-intrusive sensing has obvious advantages over many traditional procedures, as the flow field is not perturbed by the presence of a sensor. Optical sensors have the capability of gathering data in hostile environments and over larger local areas than traditional devices. Passive optics often are relatively simple, thus enhancing maintainability. Photodiodes offer fast response, low power requirements, and spectrally tunable operation. These devices offer high spatial, temporal and spectral resolutions for temperature, velocity and specie concentration measurements. Early non-intrusive techniques include schilieren and shadowgraphs provided high spatial resolution of density gradients, but were limited by line of sight restrictions of the equipment. Today's laser based systems alleviates some of these restrictions although each method had its own set of advantages and disadvantages (Mayinger-01, Kiel-01, Gord-01).

This chapter's discussion follows a somewhat different pattern vs. Chapter 2. Because of their inherent capability to measure a number of quantities, the technologies discussed here are not segregated by measurement variable.

Laser Doppler Anemeometry (LDA)

The general setup involves a laser beam passing through a splitter, which provides a two-beam illumination of a test volume. The beam pair share a shifted frequency, depending on the spatial displacement. The intersected scattered light is directed unto a photomultiplier whose signal is processed via an interface board. In general a number of interrogations, perhaps in the thousands, are needed for an accurate processing of velocity profiles (Ismailov-01). Planar patterns are often observed using a laser sheet an optical array of lenses focuses the laser output into a plane pattern. Such a measurement procedure would provide information for:

- a) Flow dynamics in combustion chamber fuel mixing region combustion process optimization requires fuel droplet size temporal distribution
- b) Integrated fuel mass flow rate requires droplet number density
- c) Jet characteristics high levels of stratification may occur in the jet stream: high concentrations near nozzle, a region near the conical edge, and also along a vortex edge.

In addition, instantaneous flow patterns may be visualized by using high speed Charge Coupled Device (CCD) cameras which may give a resolution as close as 3-5 microns.

Laser Doppler Velocimetry (LDV)

This technique gives accurate velocity information. Particles in a flow field are laser illuminated; the scattered light is then collected and processed. Usually, a single ray is projected through a beam splitter, and the two equal intensity beams are focused at a common point. An interference pattern is formed which is the measuring volume. A photodetector collects the scattered light, and the resulting frequency is related directly to the particle velocity. If one of the two beams is frequency shifted, even flow reversal patterns can be interrogated. LDV has the capability to measure three velocity components by using different frequencies, giving an instantaneous snap shot of the flow field (Thurow-01, Elliot-99, Lempert-96, Samimy-00). Temporal resolution remains the primary handicap of the method (McKenzie-96, Smith-98).

In practice, the frequency shift cannot be directly measured. Typically, a molecular filter consisting of a glass cell containing a gas such as iodine, is used a frequency discriminator. Due to rotational and vibrational molecular transitions of the cell gas, light transmission is a function of frequency, and gas pressure and temperature. Therefore, the light's frequency shift can be determined by scattered light's transmission through the filter.

LDV would appear to be a good candidate for exhaust nozzle flow profile assessment.

Particle Image Velocimetry (PIV)

These systems measure velocity by determining particle displacement with a pulsed laser technique (Raffel-98). Particle positions are illuminated in a plane by a laser sheet, and recorded using a digital camera. At a prescribed time segment, another pulse highlights the same plane, creating a second particle image. Using

these two images, data processing algorithms based on Fast Fourier Techniques (FFT) correlation methods determine displacements for the entire flow regime, a major result, including velocity information. An important feature is that turbulent statistics can be assessed. Separation points and re-attachment lengths can also be determined. Because of this, PIV could be a useful monitor for diffuser passages, and if line of sight issues addressed, turbine blade flow surfaces.

Phase Doppler Particle Analysis (PDPA)

This method uses light scattering interferometry. Two laser rays intersecting in the control volume create a fringe pattern. Crossing particles scatters light and projects the fringe, which is, detected at several off-axis detectors. Each detector produces a Doppler burst signal with a particle velocity dependent frequency. The phase shift between two different detectors is proportional to particle size. The method is attractive, as it requires no calibration and the two outputs: velocity and size are dependent only on laser wavelength and optical configuration. Thus the procedure is quite robust for dense particle and combustion environments.

Laser Induced Incandescence (LII)

LII is based on optical emission and absorption in the visible to mid infrared. LII measurements of particulates such as soot (Wainner-99) has been shown to be as accurate as 10(10)/m3 particle density (Quay-94, Melton-84). This is a key technique in the measurement of major specie concentration, high concentration CO and gas temperature (Xin-01, Morrell-01). Also general exhaust radiative signatures may be registered. Access to ultraviolet ranges has also been recently investigated (Brown-98, Yang-98). Laser induced incandescence is typically observed as a pulse on the order of a microsecond of grey body radiation from a particular matter that is heated to near vaporization temperatures by a pulsed laser. Energy absorption heats the surface up to 4000 K, followed by rapid cooling which depends heavily on partical size. The magnitude and decay rate of the luminescent pulse can respectively be used to determine respectively, particle concentration and size. The "two color" or dual wavelength method can perform the data processing where the temperature can be determined from the spectral distribution of the response.

Laser Induced Luminescence (LIL)

When a laser pulse heats certain reactants, they emit an excited spectra response. Using a laser which is tuned to an atomic or molecular absorption transition and subsequent detection of the emission, it is possible to infer both specie concentration and temperature. The main drawback is the so-called quenching phenomena where collisional deexcitation attenuates LIL signals, but research efforts have determined methods to minimize this effect.

Extensive research has been performed on chemiluminescent emissions from OH*, CH*, and C2* molecules (Mizutani-89, Samaniego-95). OH* and CH* have been found to be good indicators of reaction heat release rate as they exist in high concentrations in the flame zone, the former also providing good information on post combustion zone conditions. The planar induced fluorescence in OH* is an excellent flame marker (Jensen-86, Keller-87). Correlation between OH* and heat release Q, and burning rate have been studied. OH* and C2* measurements have been used to estimate flame front movement (Roby-95). The characteristic of having relatively strong emissions, which are spectrally narrow, makes these excellent characteristics for monitoring. Useful linear relations have been found between the equivalence ratio and the C2*/OH* value. The simultaneous determination of local combustion conditions such as Q and reaction zone equivalence would play a major role in active control schemes.

Combustion radicals demonstrate flame emission wavelengths in the range 305 – 515 nm. In addition, we must deal with the broadband emitter CO2* which may obscure other signals. As chemiluminescense form these radicals result from chemical reactions and have very short lifetimes compared to convective time scales, their signals provide good information on the reaction zone in a combustor. Species tracking in a linear flow path has shown to be quite accurate for velocity determinations (Sanders-00, 01, Littleton-00).

Accordingly, in addition to flame structure information, LIL and LII are useful exhaust measuring techniques.

Filtered Raleigh Scattering (FRS)

In this technique, the scattered spectrum from an illuminated flow field is passed through a vapor filter whose absorption line is tuned with the laser frequency (Elliot-92, 99, 01, McKenzie-96, Hoffman-96, Meyers-91). This improves flow visualization by filtering out strong background scattering. Key parameters controlling this application include laser intensity, frequency, and polarization properties. If the laser is tuned to the center of the absorption profile, most of the background interference will be absorbed (Miles-91). Since the Doppler shift is quite small, is possible that the particle scattering could shift completely out of the absorption line. This can be avoided by the proper selection of incident and observation angles.

FRS is a highly thought of procedure for performing multi-property measurements (Elliot-96, Forkay-96). All of the characteristics of a flow field – temperature, density, pressure and velocity have some effect on the spectral intensity of the Raleigh scattering profile. For example, density is proportional to the integrated intensity, width of scattering is related to temperature, and profile center position is correlated to the Doppler shift or the velocity (Lempert-97). The issue becomes the separation of these effects for real time flow calculations.

A proposed improvement to the methodology is using a frequency scanning technique (Elliot-01). The laser frequency is scanned across the absorption line and the subsequent scattering transmission through an iodine cell is measured. A typical setup has measurements performed at five points.

Coherent Anti-Stokes Raman Scattering (CARS)

This technique employs two or three laser beams, which excite a Raman transition in such a way that a third beam is produced. This resultant beam is related to the local specie concentration. The majority of experiments have been performed by interrogating rotational/vibrational Raman transitions with a 1000-4100/cm shift, or rotational transitions below 300/cm. The latter has the advantage of being able to detect simultaneously several species. However, the method has serious signal resolution issues. A major advantage over the LII for gas turbine applications is better possible in-situ configurations: spectral interference from background fluorescence is minimized, and a smaller detection angle is needed. However, the proper alignment of multiple laser paths is an issue.

Fourier Transform Infra Red Spectrometry (FTIR)

FTIR spectrometry is very capable nonintrusive method for measuring spectral emission signals, particularly those present in high temperature exhaust streams (Heland-97). For typical combustion temperatures, emissions from flame specie arise from thermal excitation of vibrational and rotational states in molecular ground states, the resulting spectra consisting of many closely spaced lines. Primary quantities of interest include the emission intensity of each spectrum, the transition frequency, and the particle density, which is given by the Boltzmann distribution equation. Using these relationships, temperature dependent line by line emission spectra can be determined. Thus we can simulate flame molecular emission for a given species concentration and temperature. Simple diatomic specie such as CO and NO can have their spectral line data calculated with known spectroscopic constants. FTIR can be used for specie determination in the 2000-2200/cm range for CO2, CO, NO and H2O measurements. The integrated area of four absorption lineshapes, which are only temperature dependent, can measure H2O density.

One proposal for the combustor exit temperature metric is the infrared absorption lines, primarily in the 1310-1600 nm range (Allen-98, 01). Measured absorption ratios are functions of temperature. Tunable diode lasers have been used this way by path averaging techniques, although soot presence degrades the signal to noise ratio (Wang-00).

Transient Grating Spectroscopy (TGS)

This is a technique where a media's electronic state is excited, and a temporal grating gives the wave speed of the gas. Of course this is related to the mean molecular weight and specific heat, from which temperature is derived. This is a promising procedure as point measurements could be made in the internal combustor cavity. TGS can also compensate for soot presence.

Far and Mid-infra red

Many of the discussed techniques involve measurements in the ultraviolet, visible, and near infrared section of the spectrum. Mid and far infrared could yield even greater insights in the thermal flow field; numerous species do not possess electronic transitions; however all molecules exhibit vibrational spectra which can be

accessed at longer wavelengths. Higher frequency radiation is more susceptible to beam steering. Particulates can cause large scattering losses in laser radiation during combustor transit. But suitable coherent radiation sources have been largely unavailable. Relative oscillator strengths for infrared vibrational transitions are small compared with ultraviolet and visible, limiting diagnostics to path averaged, line of sight absorption applications. The solution to these problems may be with innovative signal processing schemes such as wavelength multiplexing and derivative spectroscopes.

Even beyond infrared frequencies are so called "T waves" in the terahertz spectra (Gord-01, Nuss-98, Cheville-95). Many molecules possess appropriate rotational transitions in this range including some solids, which are opaque in other EM sections. Windowless combustors could result from this application.

High Speed Digital Imaging

Another technology involves flow field optical excitation for feature enhancement. Phase-locked imaging involves careful control between the excitation and the resulting recorded flow event. By sequentially increasing the delay between the two moments, a sequence of images are registered over a period of time. In general, a required condition is that the flow structure is highly repeatable; externally forced and periodic flow are situations which satisfies this demand. Unfortunately, gas turbine applications, which possess turbulent and combusting flow fields do not meet this specification. The time dynamics of such flows require visualization which captures an entire sequence of time resolved images. This translates into a high level of software and hardware integration. Sufficient spectral brightness must be provided and high bandwidth sensing is needed as repetitive sampling signal to noise enhancement is not possible.

High-speed imaging has been used for investigating ignition and early flame development. Film technology, which allows frame rates of over 500,000 per second, allows such observation (Amann-86, Patrie-92, Winter-88). Schlieren and shadowgraph techniques combined with laser illumination overcomes temporal resolution difficulties (Settles-01). High irradiant-short pulse lasers are capable of freezing combustion events, and can be done in a repetitive mode using acoustic-optic modulators. However relating such images quantitatively to quantities such as temperature or concentration is difficult.

Work has been done to integrate a series of flame pictures and then reconstruct a three-dimensional image of such using a surface contour interpolation algorithm. The key feature of the process is an adaptive schema for pixel assignment between background and flame front.

IV Other Methods

In recent years, other non-traditional techniques have been developed for flow measurements.

Acoustic Signals

Acoustic properties of a flow field can offer valuable insights into the fluid behavior. Modern sensor design allows simultaneous measurements of both fluid pressure and broad band noise levels. Proper design allows the filtering out of turbulent induced fluctuations. A relevant application of the technology is investigation of the interaction between impellers and diffusers in high-speed centrifugal compressors (Feld-01, Neise-75). Noise levels are measured at inlet and outlet locations. Noise power spectrums are constructed, and such information may be used in system identification plant models for use in active control procedures.

Another use of sound properties in flow diagnostics is the calculation of local sonic velocities (Avsec-01). Since the speed of sound depends on the particular medium or in our arena – gas composition, this can be a method for determining specie concentration.

Work has been done in calculating the sound spectrum of turbulent flames using equilibrium chemistry (Klein-99); the spectrum then can be described in terms of the mixture fraction at the flame front. This application is important in investigating the thermo-acoustic instability found in environments such as internal gas turbine combustion chambers. Combustion noise is one of the main contributors in an aircraft's engines sound production. Data reduction of the acoustic "explosion" pattern of combustors could enhance understanding of its internal flow dynamics (Zukowski).

Electrostatic Charge

Another technique is deploying a series of electrodes in a ring like pattern around a flow path, and with alternating current connections, the passing of charged particles creates a sinusoidal signal whose frequency is proportional to the flow rate. Some researchers have suggested this as way of determining individual flow rates of two phase flow streams (Lapini-01) and also as a system for engine health monitoring (Hensel-90, Cartwright-91, Pipe-88). Further refinement might expose this as a method for examining the droplet dynamics in a fuel injection environment.

Liquid Crystals

These substances are organic materials, which demonstrate optical and flow properties of crystals and fluids, respectively. Upon being heated, the material moves from solid to liquid crystal phase where light scattering occurs as a function of the apparent color, transparency being reached at the final liquid temperature. Crystals can be fabricated in such a way that the color transition occurs at specified points and ranges, and this transition can be digitized to eliminate the human in the loop. Advantages include durability, reliability and fast response time. They are not for high temperature applications, although future materials will likely extend the operation range.

Pressure Sensitive Paint

While its real time application may not be significant, pressure sensitive paints have proven to be a useful experimental tool (Gullman-00). These substances are stress sensitive materials, which may be color modulated, and thus highlight the pressure field in a given environment. Flow regimes which, indicate mainly static behavior, could be profiled at least to first order; more sensitive probes may then be calibrated accordingly.

Laser Thermal Tuft

This is a method similar to the use of pressure sensitive paint. A laser pulse heats a temperature sensitive liquid crystal residing on a flow surface. Advection produced isotherms are visible by the resulting color patterns in a teardrop shape, the tail pointing in the flow direction. This technology could prove useful in determining steady state flow directions, perhaps in an application such as flow direction determination in thrust vectored nozzles (Hassan-96).

Nuclear Effects

Some flow meters have been suggested which utilizes nuclear magnetic resonance (NMR). The NMR signal amplitude of a two phase mixture depends on the liquid content independent of the flow conditions.

Heat Flux Measurements

Currently, there are no efforts to monitor heat flux in most gas turbine applications. However such a reading, while in itself may not be very useful, could be utilized in a data processing scheme for enhancing the accuracy of other measurements. There are a number of devices for flux determination, the best known being the slug heat flux and Gardon gages (Fraden-97).

V Implementation

Optical diagnostics have been proven in the laboratory environment, but the technologies must be able to transition to actual field applications. It is necessary to develop high bandwidth systems, which can accommodate limited in-situ optical access. Another concern is that laboratory conditions are very well controlled and lack real world features of actual hardware. These challenges include:

Uncontrolled environmental influences such as vibration and temperature influences limited optical access and operational space

High background luminosity and other spectral interferences
Flow complications such as turbulence
Two phase flow,
Unpredicted particle formation
(A very open ended list)

A number of these concerns may be addressed by additional laboratory research, but some involve the inherent difficulties of an operational environment. Below, we will highlight a few areas of concern.

Operational Requirements

The numerous optical procedures, which we have discussed, have some critical points in common with regard to actual system usage. Probably the most critical is the line of sight requirement. These constructs require an excitation source to propagate through a media volume, and the resulting projection captured by a processing sensor. Clearly, the in-situ spacing present in typical gas turbine engines presents a formidable problem. Continued size reduction of components, particularly solid state elements, will help mitigate this issue. However, maintaining the precise optical geometry in the real environment will require insightful engineering efforts.

Maintainability will be critical. Laboratory optical surfaces require stringent levels of cleanliness, a difficult standard to maintain in a combustion flow path. To assist repair operations, modular designs will have to be formulated; in the field, alignment of a laser ray path may not be too practical.

Data Processing and Control

The mission of advanced sensor systems must be clearly defined before its design can commence. Beyond actual data logging applications such as operation and health monitoring, real time control is an area of intense interest. For this function, sensors must provide accurate on-line measurements to the controller plant.

The type of control employed will affect the system level usage of measurement signals. If only a few measurements are used, then classical feedback schemes may be employed. Device models in the control plant must have accurate time delay values, and any other nonlinearities appropriately quantified. However, if a multitude of data channels is required, then modern state space methods may be necessary as to avoid excessive order plant models. In this case, we again must have accurate sensor device quantification, primarily in the form of statistical error bounds.

The data processing architecture may involve multiple levels of applications. For example, algorithms for the processing of data such as signal filtering may be needed for quantitative interpretation of the signals. Then the control responses must be computed, and applied to the appropriate control devices such as valves or flow deflection surfaces.

Once, the sensor system mission is defined, the actual variables and their respective location points for measurements must be determined. Velocities, temperatures, species concentrations may all be determined by some type of light based system, but what sensor at what location for what purpose, is the issue. This again depends on the actual control or monitoring function; control issues such as observability and controllability may be needed analyses.

Clearly there must be work in defining the control objective function, the appropriate schema, and accurate sensor device and signal quantifiers.

Economics

One of the major advantages of many classical measurement methods is that there are cost effective, or in other words – cheap. The laser based systems are significantly more expensive, and for large-scale development, there must be a significant advance in the relative economy of scale. Operational and

maintenance costs will be higher, perhaps requiring a higher skill level in the technician work force. As the fundamental research continues, there needs to be a parallel motivation for developing affordable constructs.

VI Conclusions and Recommendations

Sensor Candidates

We focus primarily on the optics based systems. In surveying these procedures, several important features are clearly apparent.

Compactness

The test configurations involved in our survey involve rather bulky features. Some are of necessity, laser size for required power levels or current inferometer technology sizing for example. Field systems must be as small and light as possible.

Complexity

The laser systems include degrees of delicate configuring such as precision optical path alignments. Installation tolerances will be drastically affected by these requirements.

Spacing

Line of sight requirements are not inherently present in gas turbine flow passages.

Durability

The components found in the optical systems are not generally "hardened" enough for the thermal/vibratory environments present in many gas turbine applications such as jet engines

Processing

The information derived from optical interrogations must be processed via numerical algorithms. Accordingly, computing platforms must accompany the actual sensors.

Given these considerations, the following recommendations are made

- Diode lasers would be preferable to gas devices as their size and ruggedness would be applicable
 in potentially stressing environments. Their smaller power output will increase with further
 component development. Also, additional research in techniques involving material heating, such
 as chemiluminescense, may demonstrate a lower threshold of excitation radiation levels.
- Methods, which allow multiple feature measurements, should be emphasized; a PIV system, which only determines local velocity profiles would have to be joined by other sensors for, complete data tracking. For example, the Filtered Raleigh Scattering (FRS) method allows determination of multiple state variables, although the filtering optics would need further size reduction.
- High levels of accuracy are achieved from techniques which use particle tracking, such as PIV; however, some thought must be given to what material is to be tracked in a naturally occurring flow stream; the introduction of material would involve an additional subsystem, in addition to being a possible interference in the thermodynamics of the process. The exhaust stream would be a likely candidate for this type of sensor upon specification of the substance to be tracked.
- Procedures with the shortest optical lengths should receive greater attention. This will depend on further advances in camera and detector technology; elimination of external focusing optics would be a significant advance.
- While not a desirable option for current installations, future system designs might consider flow bypasses, which would allow sensing external to the primary flow path. A life cycle analysis would be necessary to determine the cost effectiveness of this design, assessing the benefits of the sensor inclusion.
- Techniques whose technical forecasts do not predict significant size reductions (such as infererometers) should be de-emphasized as near turn options
- Explore in greater depth from a system perspective, the usage of electromagnetic and acoustic sensors (Chapter 4). These systems would probably be relatively inexpensive and easy to install. Electromagnetic methods would depend on seeding which may again involve an undesirable subsystem. Acoustic methods will require additional signal processing research for quantifying the nature of sound and vibratory signals emitted throughout a gas turbine system.
- Continued monitoring of new technologies, which may enhance the sensor implementation role.
 For example, advancements in micro machines and nanotechnology could certainly accelerate field implementation via smaller subsystem developments.

Behind these recommendations, an implicit assumption is lurking. That is, we know precisely what is to be measured, and where. And to arrive at that position, we must define the purpose of the sensor system. It would be conservative to consider the most demanding measurement application, which is that of real time active control - for performance optimization, emissions reduction, etc. With this in mind, we reach what may be considered the primary recommendation of the current study.

Studies should be initiated and promoted for system level simulation and control models, using sensor component models, which represent current state of the art design. This will include the selection of gas turbine cycle models, the definition of system level objective functions, control architecture selection, baseline decisions on required variables to be interrogated and related sensor locations, and subsequent performance analysis. Such efforts will give insight on required accuracy levels, robustness of methodologies, and system optimization with respect to appropriate measurement variables. Conclusions will assist in the determining the most promising sensor candidates to further study.

Future Work Recommendations

Near term future work should include, in descending order of recommended priority:

- Sensor device modeling: for selected device constructs specify variables to be determined, quantify error performance and sensitivity with respect to conditions. Could be initiated with data already generated.
- System level simulation and performance optimization using derived device models. Define measures of merit for defined applications.
- Continue monitoring sensor developments, particularly size reduction breakthroughs and implementation issues.
- Continued development of in-house laboratory bench, use as simulation support and device accuracy assessments. Apply experimental design laws and device control software.
- Fundamental research in related thermal modeling needs particle scattering for possible non-seeded flow tracking, particle heating surface dynamics for determining minimal diode laser thresholds for luminescence excitation, flame structure interrogation, acoustic signal analysis of flow features, etc. Also note that control programs require mathematical representations of the various processes. Combustion models are particularly difficult and should receive continued attention.

Appendix A: Laboratory Configuration Summary

Here, we will highlight several experimental configurations, which explore the numerous techniques discussed earlier. The various setups share many similarities, and reflect the specific interests and goals of the particular researchers.

Fringe Patterns

A general setup is shown in Figure 1, where a test volume is illuminated with a light source - sometimes camera illumination lenses, the resulting fringe pattern imaged by a charge coupled device (CCD) camera. Appropriate optics treat the light rays before and after the interrogation volume. Given a flow impregnated with light scattering particles, fluid motion can be determined by the changes in the fringe patterns, thus yielding the velocity distribution.

Particle Image Velocimetry

Figure 2 has a typical setup for this technique. A flow test section is illuminated with a pulsed laser, the resulting images captured by the CCD. The illuminated radiation may be in beam form, or additional optics may create a laser sheet, which improves some outputs. Algorithms, which essentially compare particle motion between frames, are used to map out the flow field. System performance is enhanced if an additional optics set is employed, which uses a clever arrangement of filters for improved pixel comparison. Also, an intensifier may be used to improved CCD response.

Phase Doppler Particle Analysis

Figure 3 shows the key components for this technique. The laser beam is processed by optics which, splits the beam, and focuses both rays into the probe volume. A set of lenses directs the image into an array of photo detectors. The resulting signal is transmitted to a frequency and phase signal processor. Particles passing through the volume scatters light from the beams unto the existing fringe pattern. Each detector produces a Doppler burst signal with a frequency proportional to the particle velocity. Also, the phase shift between two different detectors is proportional to the particle size.

Laser Induced Incandescence

This is a very similar configuration as that of PIV; images from laser illuminated flow are captured by a CCD. A major difference is that the laser power is considerably higher as to achieve surface vaporization temperatures of the test particles. The optics specification is also different, as wavelength properties of the desired observations are different. When used to analyze flame structure, LII uses either a monochrometer or spectrometer configuration as shown in Figure 4.

Additional Flame Interrogation

This configuration allows several simultaneous measurements of flame properties. The pulsed laser beam is directed to a laser power meter; the beam from the CW laser is processed with a photodiode integrator. In addition, the flame may be observed with a monochrometer, CCD or both. Allen (Allen-01) and workers utilized this setup for analyzing LII spectra, soot concentrations and particle temperatures.

FTIR

The core of this rig, Figure 7, is the Michleson inferometer. The light source passes through the inferometer to the sample, the resulting spectral patterns processed via the detector apparatus. This arrangement is very effective for measuring the concentrations of species such as CO and NOx.

FRS

Figure 7 shows the utilization of filtered Raleigh scattering for observing a jet profile pattern. The technique uses an optics package with an absorption filter array; this modifies the scattered spectrum so that flow properties – temperature and velocity may be simultaneously measured.

Specie Concentration

A configuration used at Stanford University (Sanders-01) is shown in Figure 8. The two lasers are tuned to excite spectra in CH2 radical and O2 gases, the resulting signals received by the photodetectors. Such information could be used to assess the combustion dynamics of a fuel-air mixture. A similar rig employs a

beamsplitter, which offsets the two beams by a prescribed distance. The time for flow passage across the pair is registered, and velocity can then be computed.

Multiplexed Flow Interrogation

Another modification of the above configuration (Figure 9) involves sending multiplexed laser radiation across a flow path, the resulting signals are frequency resolved with a series of grates. Thus spectra interrogations may be performed simultaneously at several wavelengths.

Real Time Laser-Schlieren

Ultrafast imaging is performed using a setup similar to that shown in Figure 10. A pulsed laser propagates through a flame structure, the resulting image captured by the CCD.

In-House Configuration

An effort was made to construct an on site laboratory setup for simulating a number of the configurations studied. The core of the setup resembles that of Figure 7; the goal was to be able perform a number of experiments by minor repositioning of equipment. Procurement during this effort included:

10 MW He-Ne laser CW laser diodes (2) CCD monochrome camera 200-850 nm spectrometer Pentium 4 PC platform DC 10 video capture card Enhanced response silicon detectors digital laser photometer 25 mm PCX, DCX, & PCV lenses 25 mm prism, cylinder and achromatic lenses 4x5 cm drum lense 25 mm diode and surface mirrors 50 mm plate beamsplitter linear polarizing lense diffraction grating bandpass filters electronic mass flowmeter digital thermometer humidity/temperature meter digital pressure probe thermocouple leads air-gas probe accu flame gas burner and wing propane fuel tanks high speed jet flow nozzle

The above equipment establishes an experimental configuration, which could simulate many of the investigated rigs, and provide a baseline for future system level simulations.

Appendix B Computer Aided Engineering (CAE) Support

A number of software tools demonstrate significant utility in parallel with experimental assessments. These include

Computational Fluid Dynamics (CFD)

The ability to simulate flow environments and predict velocity and temperature distributions

General Purpose Modeling

System level modeling, the linking of components and their defining characteristics, and obtaining dynamic responses

Chemical Kinetics

Species production from combustion reactions as a function of pressure, temperature and initial concentrations

Data Reduction

Numerical processing and graphical package for data reduction requirements

Digital Control

Graphical modeling, simulation and control of experimental apparatus.

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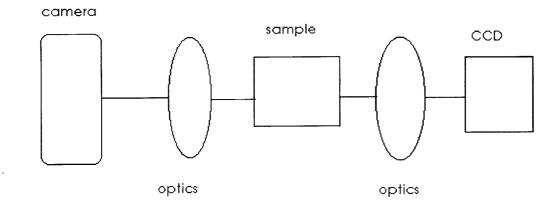
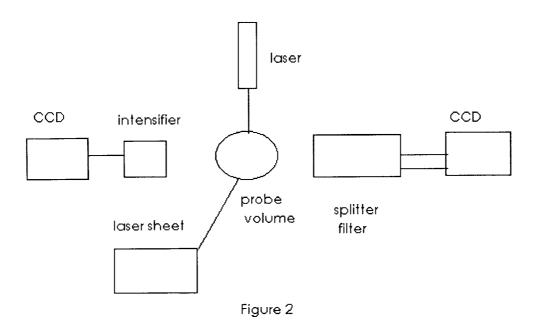
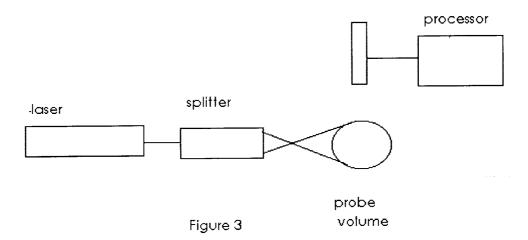


Figure 1



photodetector



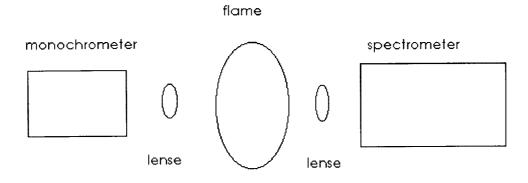


Figure 4

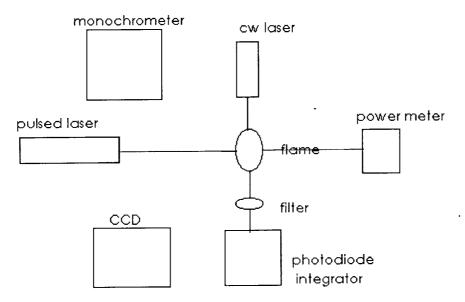


Figure 5

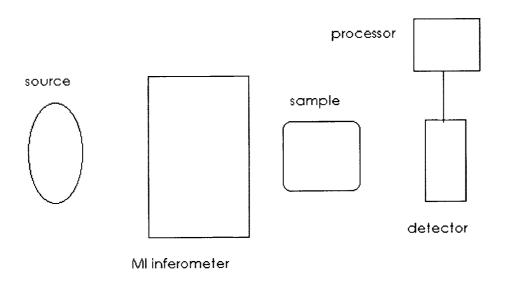


Figure 6

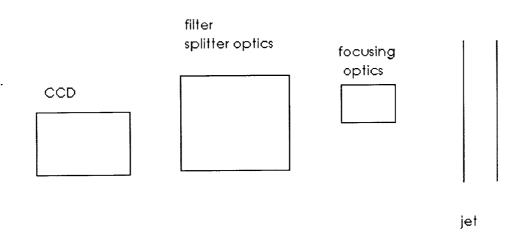


Figure 7

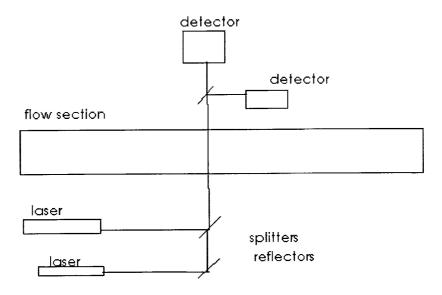
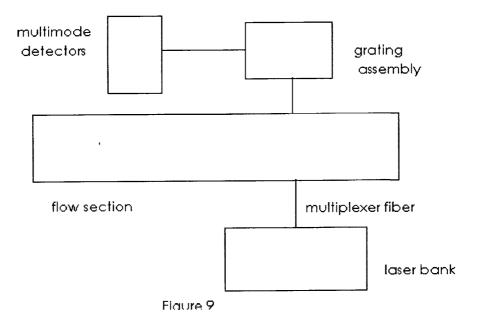


Figure 8



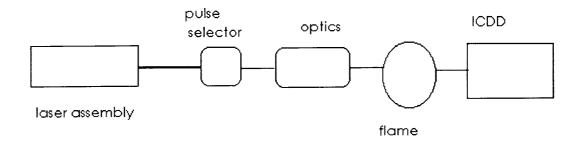


Figure 10